

MAGNETIC SUNYAEV-ZEL'DOVICH EFFECT IN GALAXY CLUSTERS

JIAN HU¹ AND YU-QING LOU^{1,2,3}

Draft version February 2, 2008

ABSTRACT

This Letter explores influences of intracluster magnetic fields ($\gtrsim 1\mu\text{G}$) submerged in the hot electron gas on classic Sunyaev-Zel'dovich effect (SZE) and thermal bremsstrahlung in X-ray emissions. As the Larmor frequency is much higher than all collision frequencies, the presence of magnetic field may lead to an anisotropic velocity distribution of hot electrons. For the two-temperature relativistic Maxwell-Boltzmann distribution, we compute modifications to the classical thermal SZE. Intracluster magnetic fields tend to enhance the SZE with steeper radial variations, which bear important consequences for cluster-based estimates of cosmological parameters. By applying the magnetic SZE theory to spectral observations of SZ and Chandra X-ray emissions from the galaxy cluster Abell 2163, a $\sim 30 - 40\mu\text{G}$ central core magnetic field B_0 is predicted. For the SZ and Chandra X-ray spectral observations of the Coma cluster, our theoretical analysis is also consistent with an observationally inferred $B_0 \lesssim 10\mu\text{G}$. As the magnetic SZE is redshift z independent, this mechanism might offer a potentially important and unique way of probing intracluster magnetic fields in the expanding universe.

Subject headings: cosmic microwave background — cosmology: theory — galaxies: clusters: general — magnetic fields — plasmas — radiation mechanisms: general

1. INTRODUCTION

The Sunyaev-Zel'dovich effect (SZE) in galaxy clusters offers a unique and powerful observational tool for cosmological studies. There has been persistent progress in detecting and imaging the SZE in clusters. In view of this rapid development in SZE observations, several important physical effects associated with the classical thermal and kinetic SZE (Sunyaev & Zel'dovich 1969, 1980) have been further explored for their diagnostic potentials, such as relativistic effects (Rephaeli 1995), the shape and finite extension of a galaxy cluster with a polytropic temperature (Puy et al. 2000), halo rotation SZE (Cooray & Chen 2002; Chluba & Mannheim 2002), Brillouin scattering (Sandoval-Villalazo & Maartens 2001), early galactic winds (Majumdar et al. 2001) and cooling flows (Schlickeiser 1991; Majumdar et al. 2001; Koch et al. 2002).

Intracluster magnetic fields have been measured using a variety of techniques and diagnostics, including synchrotron relics and halo radio sources within clusters, inverse Compton X-ray emissions from clusters, Faraday rotation measures of polarized radio sources either within or behind clusters, and cluster cold fronts in X-ray images (Clarke et al. 2001; see Carrili & Taylor 2002 for a recent review). These observations reveal that most cluster atmospheres are substantially magnetized with typical field strengths of $\gtrsim 1\mu\text{G}$ and with high areal filling factors out to Mpc radii. In the cores of 'cooling flow' clusters (Eilek & Owen 2002; Taylor et al. 2001) and at cold fronts of merging clusters (Vikhlinin et al. 2001), magnetic fields may gain intensities of $\sim 10 - 40\mu\text{G}$ and thus become dynamically important.

Magnetic fields in the intracluster gas allows for particle acceleration processes which modify specifics of heating processes, such that the electron energy distribution differs from the Maxwell-Boltzmann distribution. Such stochastic acceleration processes include shocks and magnetohydrodynamic (MHD) waves, etc. The bremsstrahlung from a modified Maxwell-Boltzmann electron gas might account for the observed X-ray spectra up to highest energies of current X-ray observations (Ensslin et al. 1999; Blasi 2000a). If energy injections by MHD waves are turned off, a galaxy cluster gradually thermalizes with electrons approaching a Maxwell-Boltzmann distribution on a rough timescale of $\sim 10^7 - 10^8$ yrs. As all collision frequencies (Nicholson 1983) are much lower than the electron Larmor frequency for the magnetized intracluster gas (Sarazin 1988), the electron velocity distribution is likely to be anisotropic as long as the parallel (relative to magnetic field \mathbf{B}) pressure is not too much higher than the perpendicular pressure (Parker 1958; Hasegawa 1975).

We presume the result of a partial electron thermalization is a two-temperature relativistic Maxwell-Boltzmann distribution, i.e. an anisotropic velocity distribution. This two-temperature does not mean an electron gas having two components with different temperatures, but refers to the same population with different average kinetic energies along and perpendicular to the local magnetic field. The main thrust of this Letter is to advance magnetic SZE theory in contexts of Chandra X-ray and radio SZE spectral observations for galaxy clusters.

In Section 2, we calculate the X-ray emission and SZE spectra using the two-temperature relativistic Maxwell-Boltzmann distribution for electron velocity. Based on both Chandra X-ray and SZ spectral observations, we offer a specific prediction for the galaxy cluster A2163. Finally, we discuss cosmological implications of our magnetic SZE theory in Section 3.

¹ Physics Department and the Tsinghua Center for Astrophysics (THCA), Tsinghua University, Beijing 100084, China.

² Department of Astronomy and Astrophysics, The University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA.

³ National Astronomical Observatories, Chinese Academy of Sciences, A20, Datun Road, Beijing 100012, China.

2. MAGNETIC SUNYAEV-ZEL'DOVICH EFFECT

Both X-ray emission and SZE spectra are sensitive to the hot electron energy distribution. By the presence of $\mathbf{B} \gtrsim 1\mu\text{G}$, electrons thermalize their parallel and perpendicular (relative to \mathbf{B}) kinetic energies separately with a resulting two-temperature Maxwell-Boltzmann distribution on timescales of $\sim 10^7 - 10^8$ yrs. We adopt a two-temperature thermal relativistic Maxwellian electron velocity distribution $p_e(\beta_1, \beta_2)$, namely

$$p_e(\beta_1, \beta_2) d\beta_1 d\beta_2 \propto \gamma^5 \beta_2 \exp\left(-\frac{\gamma_1}{\Theta_1} - \frac{\gamma_2}{\Theta_2}\right) d\beta_1 d\beta_2, \quad (1)$$

where $\Theta_1 \equiv k_B T_{\parallel}/(m_e c^2)$, $\Theta_2 \equiv k_B T_{\perp}/(m_e c^2)$, $k_B = 1.38 \times 10^{-16} \text{ erg K}^{-1}$ is the Boltzmann constant, c is the speed of light and m_e is the electron mass; T_{\parallel} and T_{\perp} are parallel and perpendicular temperatures, respectively; $\beta_1 \equiv v_{\parallel}/c$, $\beta_2 \equiv v_{\perp}/c$, $\beta^2 = \beta_1^2 + \beta_2^2$, $\gamma = (1 - \beta^2)^{-1/2}$ and $\gamma_i = (1 - \beta_i^2)^{-1/2}$ for $i = 1, 2$ with v_{\parallel} and v_{\perp} being parallel and perpendicular velocities, respectively. We assume \mathbf{B} to be random over the entire cluster on scales larger than a typical coherence length of $\sim 1 - 10 \text{ kpc}$. Thus microscopically anisotropic electrons are macroscopically isotropic, analogous to a demagnetized ferromagnet. Integrating in all directions, the electron speed or energy distribution becomes

$$p_e(\beta) d\beta = N \gamma^5 \beta d\beta \int_{-\beta}^{\beta} \exp\left(-\frac{\gamma_1}{\Theta_1} - \frac{\gamma_2}{\Theta_2}\right) d\beta_1, \quad (2)$$

where N is a normalization factor computed numerically.

The firehose stability (Parker 1958; Hasegawa 1975) for velocity anisotropy requires

$$B^2/(2\pi) \gtrsim n_e (\langle mv_{\parallel}^2 \rangle - \langle mv_{\perp}^2 \rangle) > 0, \quad (3)$$

where n_e is the electron number density, $m \equiv \gamma m_e$, angled brackets indicate averages over $p_e(\beta)$ and the mean temperature T is defined by $3k_B T/2 \equiv (2\langle mv_{\perp}^2 \rangle + \langle mv_{\parallel}^2 \rangle)/2$. It then follows that

$$k_B T_{\parallel} \equiv \langle mv_{\parallel}^2 \rangle = k_B T + B^2/(3\pi n_e), \\ k_B T_{\perp} \equiv \langle mv_{\perp}^2 \rangle = k_B T - B^2/(6\pi n_e)$$

with $B^2/(2\pi n_e k_B)$ being the upper bound for the temperature difference $T_{\parallel} - T_{\perp}$. For an observed X-ray energy spectrum and an empirically inferred B distribution in a cluster, one may estimate T_{\parallel} and T_{\perp} by fitting the spectral data. By correlations between X-ray surface brightness and Faraday rotation measure (Dolag et al. 2001), a power law $B \propto [n_e(r)]^{\alpha}$ was inferred with an exponent α estimated from the slope of $\ln B$ versus $\ln n_e$ relation. For example, one finds $\alpha \sim 0.9$ for the galaxy cluster A119 and $\alpha \sim 0.5$ for the galaxy cluster 3C 129 with a larger uncertainty in the latter. For $\alpha = 0.5$, T_{\parallel} and T_{\perp} can remain constant in a magnetized galaxy cluster.

The X-ray emission rate per unit volume per unit energy interval is given by

$$j_X(E_X) = n_e^2 c \int d\beta p_e(\beta) \beta \sigma_B(\beta, E_X), \quad (4)$$

where $\sigma_B(\beta, E_X)$ is the differential cross section (Haug 1997) for the bremsstrahlung of an X-ray photon with

energy E_X from an electron of speed $c\beta$. Given a central B_0 , we fit an observed X-ray energy spectrum with the electron distribution (2) and $T_{\parallel} - T_{\perp}$ constrained by marginal firehose stabilities (Parker 1958; Hasagawa 1975).

To scatter a cosmic microwave background (CMB) photon (Birkinshaw 1999) of frequency ν_i off an isotropic distribution of thermal electrons with speed $c\beta$, the probability for the scattered photon of frequency $\nu_i(1+s)$ is

$$P(s, \beta) = \frac{3}{16\gamma^4 \beta} \int_{\mu_1}^{\mu_2} \frac{(1 + \beta\mu')}{(1 - \beta\mu)^3} \\ \times [1 + \mu^2 \mu'^2 + (1 - \mu^2)(1 - \mu'^2)/2] d\mu, \quad (5)$$

with $\mu' \equiv [(1+s)(1 - \beta\mu) - 1]/\beta$, where $\mu_1 = (s - \beta)/[(1+s)\beta]$ and $\mu_2 = 1$ for $s \geq 0$ and $\mu_1 = -1$ and $\mu_2 = (s + \beta)/[(1+s)\beta]$ for $s < 0$. As the intracluster electron gas is macroscopically isotropic and has a thin optical depth $\tau_e \sim 10^{-2}$, integral (5) is applicable to the magnetic SZE analysis. For photons scattered by an electron distribution of expression (2), the resulting distribution in the fractional frequency shift s is

$$P_1(s) = \int_{s/(2+s)}^1 d\beta p_e(\beta) P(s, \beta). \quad (6)$$

For CMB photons scattered by a hot intracluster electron gas, the change in the CMB spectrum at frequency ν caused by the magnetic SZE is

$$\Delta I(\nu) = \frac{2h\nu^3}{c^2} \tau_e \int_{-1}^{+\infty} ds \left[\frac{P_1(s)(1+s)^3}{e^{(1+s)x} - 1} - \frac{P_1(s)}{e^x - 1} \right], \quad (7)$$

where $x \equiv h\nu/(k_B T_{\text{CMB}})$, $h = 6.63 \times 10^{-27} \text{ erg s}$ is the Planck constant, T_{CMB} is the present CMB temperature and $\tau_e = \sigma_T N_e$ with $\sigma_T = 6.65 \times 10^{-25} \text{ cm}^2$ being the electron Thomson cross section (Rybicki & Lightman 1979) and N_e being the column density of free electrons along the line of sight.

In the extensively used beta-model for intracluster hot electron gas (Sarazin 1988; Fabian 1994), the empirical radial distribution of $n_e(r)$ is

$$n_e(r) = n_{e0} [1 + (r/r_c)^2]^{-3\beta_c/2}, \quad (8)$$

where r_c is the core radius and n_{e0} is the central electron number density. It follows that τ_e at radius r is given by

$$\tau_e(r) = \tau_{e0} [1 + (r/r_c)^2]^{(1-3\beta_c)/2}, \quad (9)$$

where $\tau_{e0} = n_{e0} \sigma_T r_c \sqrt{\pi} \Gamma(3\beta_c - 1/2)/\Gamma(3\beta_c)$ and Γ is the gamma function.⁴ We use eqns. (2), (5), (6) and (9) in integral (7) to compute magnetic SZE spectrum at r .

For spectral observations of A2163, we estimate the lower limit of intracluster B from data using our magnetic SZE theory. Being one of the hottest clusters, the thermal electron gas trapped in A2163 (redshift $z = 0.203$) has a mean temperature $k_B T_c \simeq 12.4 \pm 0.5 \text{ keV}$ and a central density $n_{e0} \simeq 6.82 \times 10^{-3} \text{ cm}^{-3}$ with a core radius $r_c = 0.269 \pm 0.025 \text{ Mpc}$ (Hubble constant $h_{100} = 0.71$) and a $\beta_c = 0.616 \pm 0.031$ (Elbaz et al. 1995; Markevitch et al. 1996; Markevitch & Vikhlinin 2001). By these estimates, the optical depth towards the

⁴ Here, β_c instead of β is used to avoid notation confusions with the dimensionless thermal electron speed β .

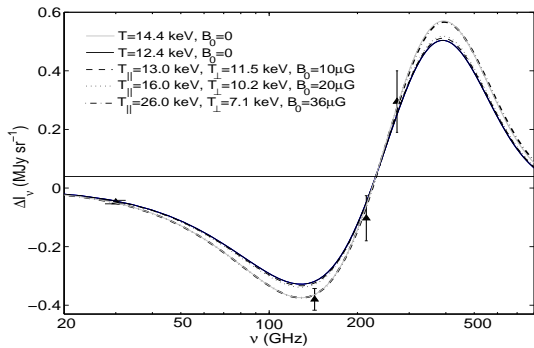


FIG. 1.— The SZE spectrum of A2163 (triangles with error bars are data points). The heavy solid line ($T = 12.4$ keV) is the thermal SZE with parameters determined from X-ray observations with $B_0 = 0$. The dash, dotted and dash-dotted lines represent magnetic SZE with different central magnetic field strengths B_0 and with other cluster parameters being the same. We take $\alpha = 0.5$, so that T_\perp and T_\parallel remain constant in the cluster. The grey line ($T = 14.4$ keV, $B_0 = 0$) coincides with the dash-dotted line.

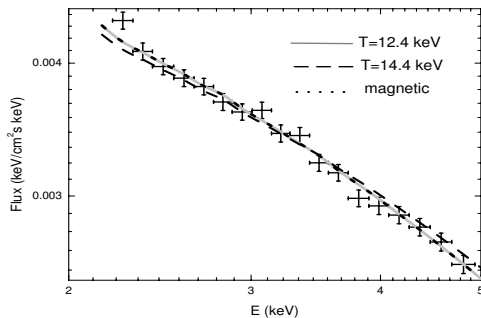


FIG. 2.— Energy spectrum of the central $r \lesssim 5'$ region of A2163 by Chandra. The grey and dashed lines are the $T = 12.4$ and 14.4 keV thermal bremsstrahlung fits. The dotted line shows our magnetic model of essentially the same fit as $T = 12.4$ keV yet with different B_0 , T_\parallel and T_\perp of Fig. 1. The lower energy part ($\lesssim 2.1$ keV) is contaminated by the soft excess (Markevitch & Vikhlinin 2001). The spectral resolution for energy $\gtrsim 5.0$ keV is not high enough and is blended with the Fe K_α line (peaked at 5.3 keV for $z = 0.203$). We fit the 2.1 – 5.0 keV band with uncertainty in T of 0.9 keV (90%CL).

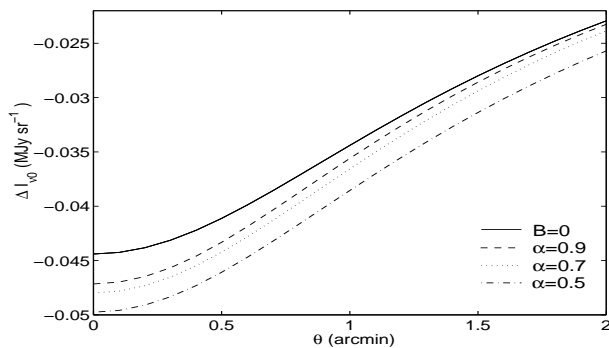


FIG. 3.— Radial features of thermal and magnetic SZE models for A2163 at $\nu_0 = 30$ GHz. The solid line is the thermal SZE, the dash, dotted and dash-dotted lines are models with the same central magnetic field strength $B_0 = 36 \mu\text{G}$ but different α values.

cluster center is $\tau_{e0} = 0.0133$ and the central Compton parameter is $y_{th0} = 3.21 \times 10^{-4}$.

A conspicuous SZE spectrum has been observed in A2163 at four frequencies by BIMA at 30GHz (LaRoque et al. 2002), by DIABOLO at 140GHz (Desert et al. 1998) and by SuZIE at 140, 218 and 270GHz (Holzapfel et al. 1997) with dust-corrections (LaRoque et al. 2002). These data were previously fit with a Compton parameter $y_{th} = (3.56^{+0.41+0.27}_{-0.41-0.19}) \times 10^{-4}$ for a thermal SZE together with a kinetic SZE for a positive peculiar velocity $V_p = 415^{+1030+460}_{-850-440}$ km s $^{-1}$ (68%CL) (Carlstrom et al. 2002). A positive-velocity kinetic SZE leads to an overall downward shift of the thermal SZE spectrum especially around the zero point (~ 218 GHz) of the SZE.

We fit the observed X-ray spectrum of Fig. 2 for a mean temperature $T \cong 12.4$ keV by eqns. (2) and (4) with different B strengths and infer relations among B , T_\parallel and T_\perp . We here take $\alpha = 0.5$ with T_\perp and T_\parallel being constants (see parameters of Fig. 1). Inserting these relations into eqns. (2), (6) and (7), we obtain the spectra of magnetic SZE.

Shown in Fig. 1 are SZE spectra computed for A2163 with different parameters in comparison with the observed SZE spectrum. The model without magnetic field (solid line for $T = 12.4$ keV) underestimates signals of SZE (especially at $\nu = 140$ GHz) with $\chi^2 = 3.82$ in a chi-square fit. Intracuster magnetic field tends to enhance signals of SZE and the best fit is $B_0 = 36 \mu\text{G}$ with $\chi^2 = 0.78$. As the marginal firehose stability (Parker 1958) is used here, the fitting estimate represents the lower limit of $B_0 = 36 \mu\text{G}$ for A2163. Magnetic field also increases the null frequency of the pure thermal SZE, similar to the kinetic SZE with a positive velocity. This degeneracy can be removed by SZE signals at other frequencies (e.g. 100 and 400 GHz, etc.). The SZE spectrum data can be fit with $T = 14.4$ keV (grey line in Fig. 1) and $B_0 = 0$, but the thermal spectrum data does not fit well with $T = 14.4$ keV (dashed line in Fig. 2). Shown in Fig. 3 are computed radial SZE features of thermal ($B = 0$) and magnetic ($\alpha \neq 0$) SZE models for cluster A2163 at 30 GHz. With a smaller exponent α , SZE signals steepen from the central to peripheral parts of a cluster. This can be utilized to determine macroscopic mean \mathbf{B} structures by obtaining spatially resolved magnetic SZE intensity maps (Carlstrom et al. 2002). Note that 30 GHz of Fig. 3 is just an illustrating example.

3. DISCUSSIONS

Contrary to recent results (Koch et al. 2003; Zhang 2003), we find that the anisotropic velocity distribution of electrons caused by magnetic field B enhances the SZE. Our model results of Figs. 1 – 3 can be critically tested against more precise spectral SZE measurements of A2163 in the frequency bands of $\sim 50 - 130$ GHz and $\sim 300 - 600$ GHz by MAX, MSAM and SuZIE types of experiments in the frequency passbands of 90 – 670 GHz and by AMiBA in the band 84 – 104 GHz, Nobeyama at 21 and 43 GHz, JCMT at 350 and 650 GHz, SZA in the bands of 26 – 36 GHz and 85 – 115 GHz, BIMA and OVRO in the band of 26 – 36 GHz, MINT at 150 GHz and ACT at 150, 220, and 270 GHz. Multi-frequency projects such as the upgraded MITO (Lamagna et al. 2002; De Petris et al. 2002) and the OLIMPO (Masi et al. 2003) experiments are very promising to provide some results.

A2163 may involve merger shocks that could amplify B (e.g. Markevitch & Vikhlinin 2001). The spectral index maps of A2163 show a spectral steepening from the central to peripheral radio halo regions, implying a radial decrease of B in reacceleration models (e.g. Feretti et al. 2003). It was attempted to fit the SZE spectrum of A2163 with a combination of thermal and non-thermal electrons (e.g. Colafrancesco et al. 2003), but no evidence was found for hard X-ray excess due to the non-thermal component in the BeppoSAX data (e.g. Feretti et al. 2001).

Based on X-ray and SZE measurements, 41 galaxy clusters were used to independently estimate Hubble constant $h_{100} = 0.61 \pm 0.03 \pm 0.18$, where the uncertainties are statistical and systematic at 68% confidence level for $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ cosmology (Carlstrom et al. 2002; Reese 2003). Our analysis of A2163 shows that intracluster magnetic field induces microscopic anisotropies in electron velocity distribution to enhance the SZE. It appears that inferences from cluster models without magnetic field would systematically underestimate h_0 as in the case of A2163 for which Holzapfel et al. (1997) inferred a lower $h_{100} = 0.60 \pm 0.04$ against the current WMAP result of $h_{100} = 0.71 \pm 0.04$. As the cluster asphericity and orientation in the sky are random and the average cluster peculiar velocity is zero, these factors should contribute to the systematic uncertainty with the Hubble constant being statistically unaltered. The underestimation of Hubble constant may be explained by the generic presence of core magnetic field $B_0 \sim 10 - 40 \mu\text{G}$ in this sample of galaxy clusters.

Another important cosmological effect of the ubiquitous enhancement of magnetic SZE due to the prevalence of $\gtrsim 1 \mu\text{G}$ magnetic fields in galaxy clusters would be observable in the CMB angular spectrum especially at high

$l \gtrsim 3000 - 4000$. This contribution to CMB fluctuations may be estimated and tested by CMB experiments such as ACT, Planck, SZA, etc. Details of these two cosmological effects will be pursued in forthcoming papers.

For X-ray (Arnaud et al. 2001) and SZE (De Petris et al. 2002) spectral observations of Coma cluster (Abell 1656), our magnetic SZE analysis is consistent with the currently inferred $B_0 \lesssim 10 \mu\text{G}$ (Carilli & Taylor 2002). Likewise, magnetic SZE can be utilized in other galaxy clusters with high-resolution and high-sensitivity X-ray and SZE spectral observations to estimate the lower limit of B_0 as well as SZE spatial features. While it is necessary to estimate all possible corrections to the classic SZE in order to isolate the magnetic contribution, this may be a unique procedure to probe intracluster magnetic fields at high redshifts z , at least statistically. Finally, anisotropic distributions of nonthermal electrons should lead to distinct magnetic SZE in radio lobes of extragalactic jets.

We thank the referee Dr. D. Puy for useful comments. This research has been supported in part by the ASCI Center for Astrophysical Thermonuclear Flashes at the U. of Chicago under DOE contract B341495, by the Special Funds for Major State Basic Science Research Projects of China, by the THCA, by the Collaborative Research Fund from the NSF of China for Outstanding Young Overseas Chinese Scholars (NSFC 10028306) at the National Astronomical Observatory, CAS, by NSFC grant 10373009 at the Tsinghua U., and by the Yangtze Endowment from the Ministry of Education through the Tsinghua U. Affiliated institutions of YQL share this contribution.

REFERENCES

- Arnaud, M., et al. 2001, *A&A*, 365, L67
 Birkinshaw, M. 1999, *Phys. Rep.*, 310, 97
 Blasi, P. 2000a, *ApJ*, 532, L9
 Blasi, P. Olinto, A. V., Stebbins, A. 2000b, *ApJ*, 535, L71
 Carlstrom, J., Holder, G., Reese, E. 2002, *ARA&A*, 40, 643
 Carilli, C. L., Taylor, B. 2002, *ARA&A*, 40, 319
 Chluba, J., Mannheim, K. 2002, *A&A*, 396, 419
 Clarke, T. E., Kronberg, P. P., Böhringer, H. 2001, *ApJ*, 547, L111
 Colafrancesco, S., Marchegiani, P., Palladino, E. 2003, *A&A*, 397, 27
 Cooray, A., Chen, X. 2002, *ApJ*, 573, 43
 De Petris, M. et al. 2002, *ApJ*, 574, L119
 Desert, F. et al. 1998, *New Astron.*, 3, 655
 Dolag, K. et al. 2001, *A&A*, 378, 777
 Eilek, J.A., Owen, F.N. 2002, *ApJ*, 567, 202
 Elbaz, D., Arnaud, M., Böhringer, H. 1995, *A&A*, 293, 337
 Fabian, A. C. 1994, *ARA&A*, 32, 277
 Feretti, L. et al. 2001, *A&A*, 373, 106
 Feretti, L. et al. 2003, The Cosmic Cauldron, 25th IAU meeting
 Haug E. 1997, *A&A*, 326, 417
 Hasegawa, A. 1975, *Plasma Instability and Nonlinear Effects*, Springer-Verlag, Berlin
 Holzapfel, W. L. et al. 1997, *ApJ*, 480, 449
 Kaiser, N. 1986, *MNRAS*, 222, 323
 Koch, P. M., Jetzer, Ph., Puy, D. 2002, *New Astron.*, 7, 587
 Koch, P. M., Jetzer, Ph., Puy, D. 2003, *New Astron.*, 8, 1
 Lamagna, L. et al. 2002, *AIP Conf. Proc.* 616, 92
 LaRoque, S. J. et al. 2002, *ApJ*, submitted (astro-ph/0204134)
 Majumdar, S., Nath B. Chiba M., 2001, *MNRAS*, 324, 537
 Markevitch, M. et al. 1996, *ApJ*, 456, 437
 Markevitch, M., Vikhlinin A. 2001, *ApJ*, 563, 95
 Masi, S. et al. 2003, *Mem.S.A.It* 74, 96
 Nicholson, D. R. 1983, *Introduction to Plasma Theory*, Wiley, New York
 Parker, E. N. 1958, *Phys. Rev.*, 109, 1874
 Puy, D., Grenacher, L., Jetzer, Ph., Signore, M. 2000, *A&A* 363, 415
 Reese, E. D. 2003, *Measuring and Modeling the Universe*, ed. W. L. Freedman (Cambridge: Cambridge Univ. Press)
 Rephaeli, Y. 1995, *ARA&A*, 33, 541
 Rosati, P., Borgani, S., Norman, C. 2002, *ARA&A*, 40, 539
 Rybicki, G. B., Lightman, A. P. 1979, *Radiative Processes in Astrophysics*, Wiley, New York
 Sandoval-Villalazo, A., Maartens, R. 2001, astro-ph/0105323
 Sarazin, C. 1988, *X-Ray Emission from Clusters of Galaxies*, Camb. Univ. Press, Cambridge
 Schlickeiser, R. 1991, *A&A*, 248, L23
 Sunyaev, R. A., Zel'dovich, Y. B. 1969, *Ap&SS*, 4, 301
 Sunyaev, R. A., Zel'dovich, Y. B. 1980, *ARA&A*, 18, 537
 Taylor, G. B., Fabian, A. C., Allen, S. W. 2002, *MNRAS*, 334, 769
 Vikhlinin, A., Markevitch, M., Murray, S. S. 2001, *ApJ*, 549, L47
 Zhang, P. J. 2003, astro-ph/0308354